Bodo Ruck

Interaction of severe convective gusts and typical urban structures

B. Ruck, A. Bertsch
Laboratory of Building- and Environmental Aerodynamics, Institute for Hydromechanics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
e-mail: ruck@kit.edu

1. Introduction

As reported in literature, wind speeds of over 70 m/s can be reached in downdrafts of thunderstorms, see Fujita 1990, leading to thunderstorm outflow velocities at the ground of over 200 km/h. Thus, wind speeds of thunderstorm outflows can exceed those related to synoptic-scale winter storms. The research in the field of downdrafts has been performed in the past mainly by meteorologists. In order to understand the formation of downdrafts, concerted research campaigns have been performed (NIMROD 1978, JAWS 1982, MIST 1986), see Fujita 1979, 1981, McCarthy et al. 1982 and Dodge et al. 1986. In these campaigns, detailed information could be obtained about characteristic sizes of macro- and microbursts, see Hjelmfelt 1988, however, a precise temporal and spatial characterization of the resulting near ground winds is still missing. Convective gusts may have severe implications in engineering. From an engineering perspective, thunderstorm outflow velocities can exceed design wind velocities given in wind loading codes and national building standards and may cause considerable damages to buildings and critical urban infrastructure. Unfortunately, essential meteorological information concerning probability, spatial extent and maximum speed of convective gusts is rare. Furthermore, due to the fact that convective gusts are of local-scale nature, it is believed that they are underrepresented in wind statistics of meteorological stations. Beside this lack of knowledge, another crucial and so far not investigated field is the interaction of convective gusts with urban structures. Typical city ‘roughness elements’ like street canyons, squares, crossings, parks etc. can funnel thunderstorm outflows and even amplify their strength locally. In the present paper, first results of the research program ConWinG are described concerning the interaction of convective gusts with typical urban structures.

2. Downdraft interaction

Buildings and structures are designed against wind loads on the basis of national or international wind loading codes (e.g. EUROCODE, DIN EN 1991-1-4,#ASCE7). In the codes, certain lay-out wind velocities at reference heights are given depending on the kind of wind exposure defined by wind zone and surface roughness. Additionally, logarithmic or exponential laws are given to define the local vertical profile of flow quantities like e.g. mean velocity or dynamic wind pressure. Wind loading codes presume a horizontal wind and do not consider a vertical wind component of the approach flow.

The lay-out of structures by national standards does usually not consider the interaction of downdrafts with urban structures. Typically, wind gusts induced by downdrafts lead to high velocities near the ground and generate wall-jet-like wind profiles. When compared to the flow of an atmospheric boundary layer (ABL), these wall-jet-like winds show fundamental differences concerning their non-steady flow behavior, their wind profile with height, their complex 3d-structure and their lower level of turbulence. In this context, it should be emphasized that the ‘mean’ wind profile of a downdraft outflow is a function of location and time unlike the mean velocity profile in the ABL.

According to Fujita 1990, a downburst is a column of descending air impacting on the ground and bursting out radially. At the leading edge of the impinging and diverging flow, a primary vortex forms immediately. If the ground is plane and flat and if the direction of the descending air is perpendicular to the surface, the radial outburst is rotationally symmetric. The size or the spatial extension of convective gusts or downdrafts varies from a few tens of meters to several kilometers. Small events have a shorter life time in contrast to larger events. Very strong gusts (macrobursts) show a horizontal extension of more than 4 km. Microbursts are events with a horizontal extension of 0.4 to 4 kilometers and have an average life of 5 to 15 minutes. Of course, also smaller convective gusts exist, however, due to their limited spatial and temporal extent, only very few information exists. From field measurements and numerical simulations, see Kim & Hangan 2007, it can be inferred that the maximum velocity in the profile of a downdraft outflow over plane ground is in a height of about 5% of the initial downdraft column diameter. This means e.g. that for a microburst of the order of 500 m in diameter, the maximum velocity occurs in a height of about 25 m.

If the touch down location of a downdraft is a built area, then, urban structures can prevent the flow from spreading in all directions and can even amplify the already high downdraft velocity by funneling effects. This phenomenon is apparently not treated by national or international wind loading standards, which only consider the interaction of single buildings in free and undisturbed approach flow without interference effects of surrounding structures. Fig. 1 shows a downburst over Salzburg/Austria (left side) and the fundamental difference in profile of ABL- and downdraft wind profile near the ground (right side). Concerning the interaction of convective gusts with built structures, only few reports exist (Chay & Letchford 2002, Letchford & Chay 2002, Savory 2001). In their two-part work Chay & Letchford 2002 showed that both, the specific velocity profile of downburst as well as its unsteady behavior yields pressure distributions on individual buildings, which differ from the ones obtained in conventional atmospheric boundary layer flow.

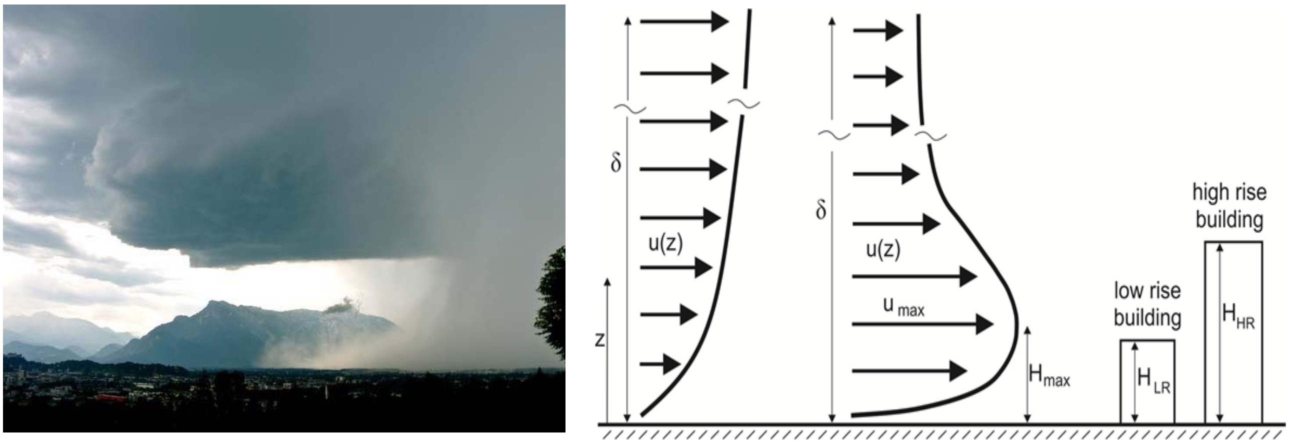


Fig. 1: left: Downburst over Salzburg on June 22, 2011 (Foto: Fabian Lackner) right: Schematic of an atmospheric boundary layer profile and the velocity profile in the outflow of a downburst

3. Experimental details

In the frame of ConWinG, an experimental set-up is built in order to investigate the interaction of downdrafts with typical urban structures, see Fig. 2 for a sketch of the final version. The experiments are conducted at the Laboratory of Building- and Environmental Aerodynamics at the Karlsruhe Institute of Technology (KIT), Germany. As can be seen in Fig. 2, an atmospheric boundary layer flow is established in a Goettinger-type wind tunnel and typical urban structures (street canyon, crossings and squares with ambient buildings) shall be modelled in the measuring section.

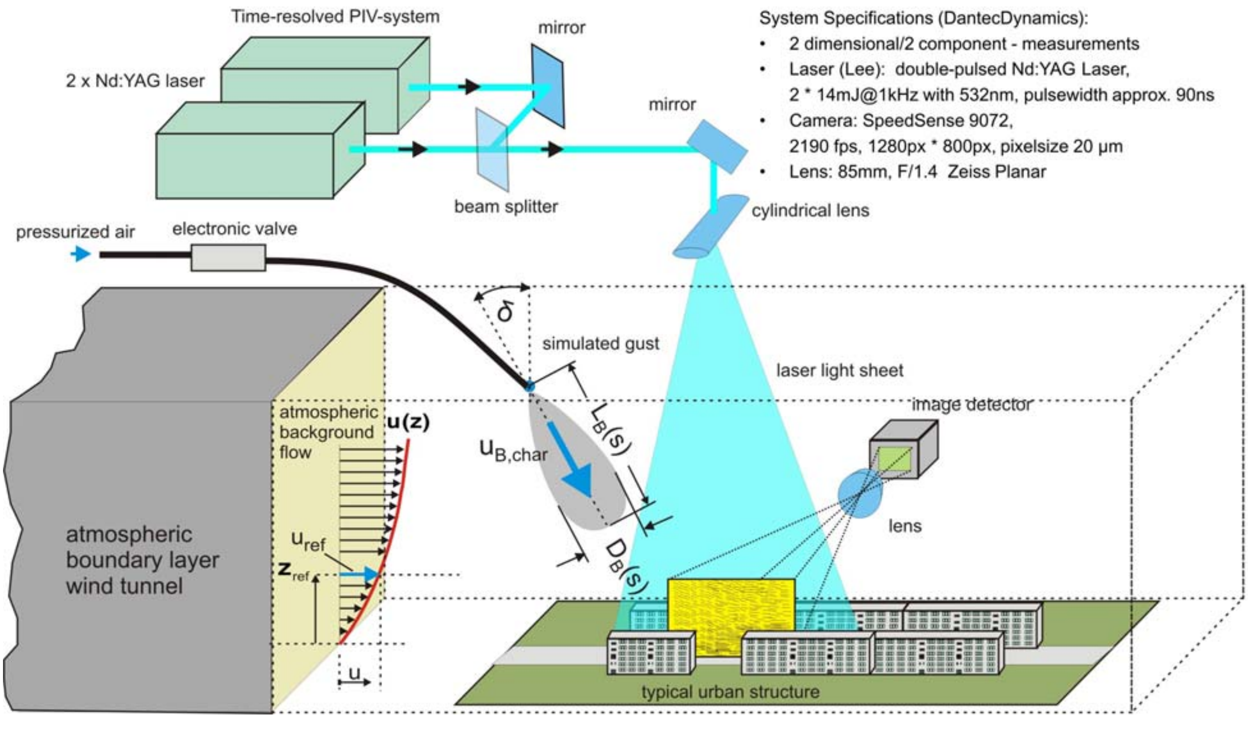


Fig. 2: Sketch of the experimental set-up consisting of boundary layer wind tunnel, gust generator, 2D-2C-TR-PIV system and urban built structure

To measure the flow field, a 2D-2C TR-PIV system is used. This system is equipped with a Nd:YAG laser and a high speed camera. The camera can acquire up to 2190 fps at full resolution with a 1280 x 800 pixel CMOS-Sensor (pixel size = 20 x 20 µm²). The velocity is recorded with a frequency of 500 Hz in double frame mode (i.e. 1000 images per second). To synchronize all the measurement facilities (i.e. laser, valve, camera) a digital synchronizer is used. The overlaying downdraft is simulated by a continuous or pulsed wall jet ejected from a tube connected to pressurized air.

Urban structures can have an infinite variety with respect to building height, alignment and combination. Thus, typical urban structures must be identified and simplified. In the frame of ConWinG, the interaction of convective gusts with 4 different configurations shall be investigated, see Fig. 3. The models are mounted on a wooden plate that can be rotated to position the street canyon in different angles β relative to the wind tunnel flow.

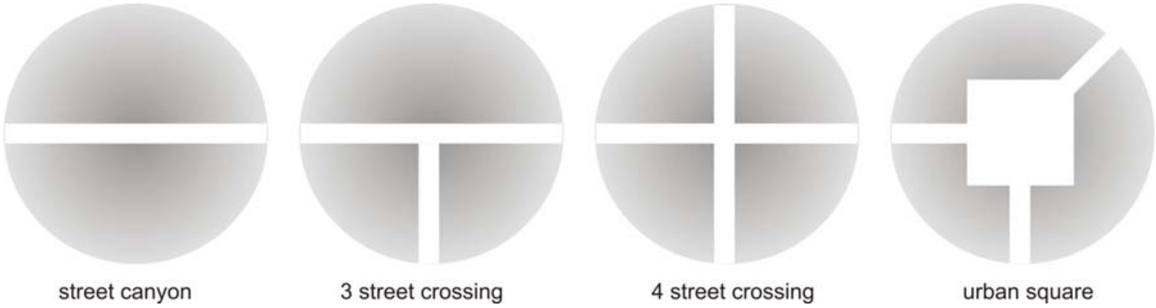


Fig. 3: Sketch of the simplified urban structures chosen for the investigation

4. Configuration street canyon

The project ConWinG started in 2014 and is running for three years, thus the present paper refers only to the first configuration of a street canyon. Fig. 3 gives a photograph of the specific street canyon setup. The outlet of the tunnel was equipped with triangle-shaped spires and roughness elements to simulate an atmospheric boundary layer. The diameter D of the jet tube was 10 mm. The pressurized air was controlled by a fast pneumatic valve and a pressure regulator. The jet was injected from above perpendicular to the wind tunnel flow. The street canyon model was open on the backside and the wall within the street canyon towards the camera was made of glass. Thus, the camera was able to record the measurement field through the model walls without tilting.

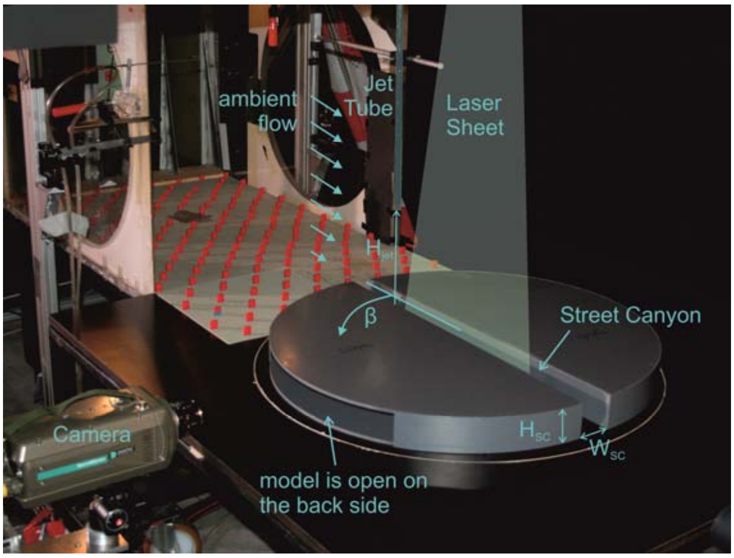


Fig: 4: Experimental setup with the street canyon

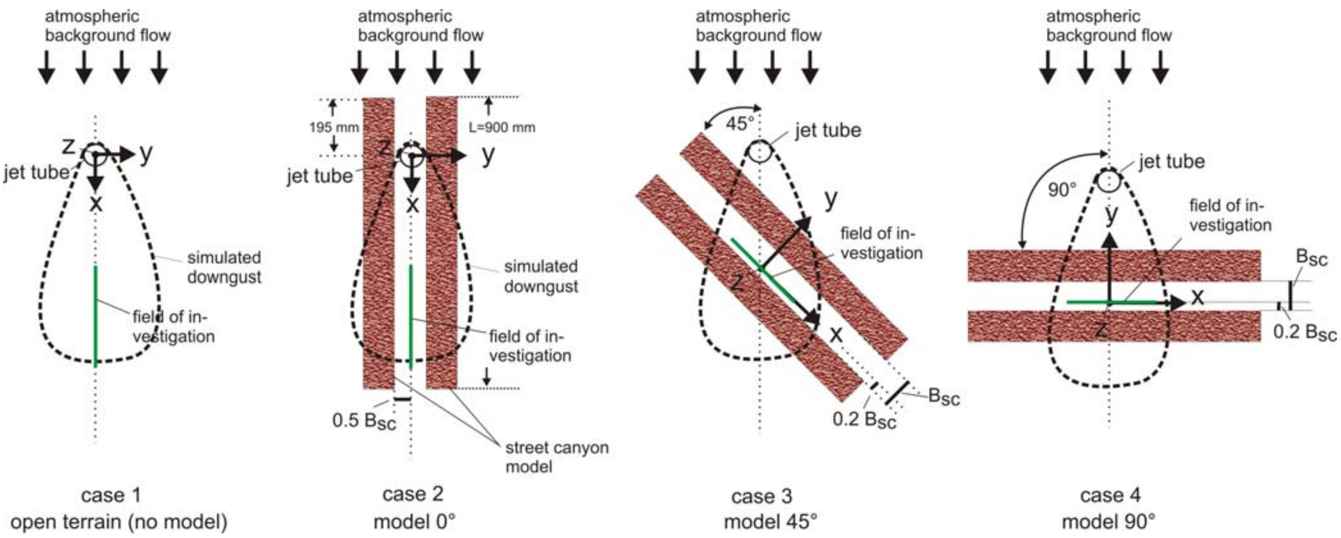


Fig. 5: Investigated cases for street canyons

The street canyon model had a height of H_{SC} = 75 mm and a width of B_{SC} = 50 mm. With a scale of 1:200 this corresponds to a road width of 10 m and a building height of 15 m. When the jet approached the model, its diameter was about 150 - 200 mm and, therefore, corresponds to a down-gust with a diameter of about 30 - 40 m. In the following analysis a height of zref = 50 mm (i.e. 10 m in nature) was chosen as reference height. The variations investigated are given in Fig. 5.

The jet outlet was positioned at H_{Jet} = 310 mm above the plate. V_{amb} = 3 m/s is the velocity of the wind tunnel flow in the upper part of the tunnel (i.e. it corresponds to u(δ)). V_{Jet} =45 m/s is the maximum velocity at the outlet of the gust injection tube. Note that this value does not relate to any velocity in nature (in order to ensure dynamic similarity, the ratio of momentum force of impinging jet to momentum force of background wind at the location of investigation is crucial).

5. Results of TR-PIV measurements

The results refer to a street canyon exposed to an atmospheric background flow and a downdraft. All profiles were normalized by the same reference velocity. For this, the horizontal velocity of the background flow without any model (flat and open terrain) was chosen at the reference height z_{ref}. All lengths were normalized by the reference height z_{ref} = 50 mm (i.e. 10 m in nature). The height of the street canyon corresponds to z/z_{ref} = 1.5.

In Fig. 6, the profiles of the experiment without canyon model are shown. Thus, this case describes the pure interaction of an atmospheric boundary layer flow and an impinging jet on flat terrain. The u-profiles show first a kind of waist or nose profile which is due to the deflection of the jet by the ambient wind. Up to x/z_{ref} < 3, the profile can be considered as a vertical cross-section through the jet. In this section, there's almost no interaction with the wall. For larger values of x/z_{ref} higher horizontal velocities occur, whereas the peak value is too close to the ground plate to be measured. The highest horizontal velocities occur at $x/z_{ref} \approx 4$.

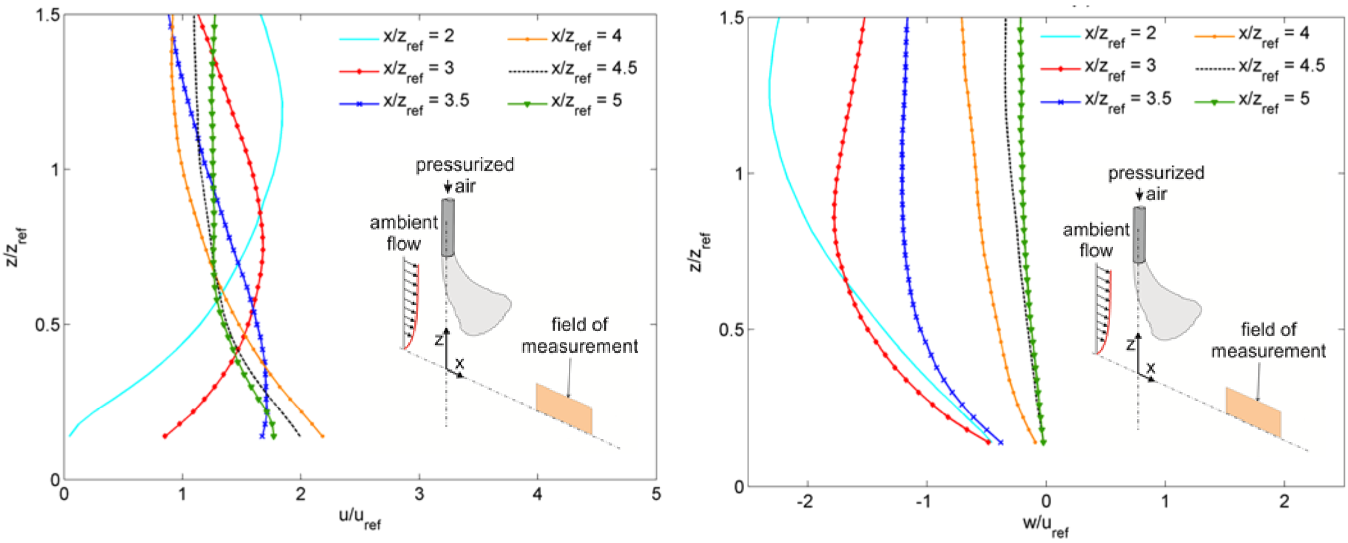
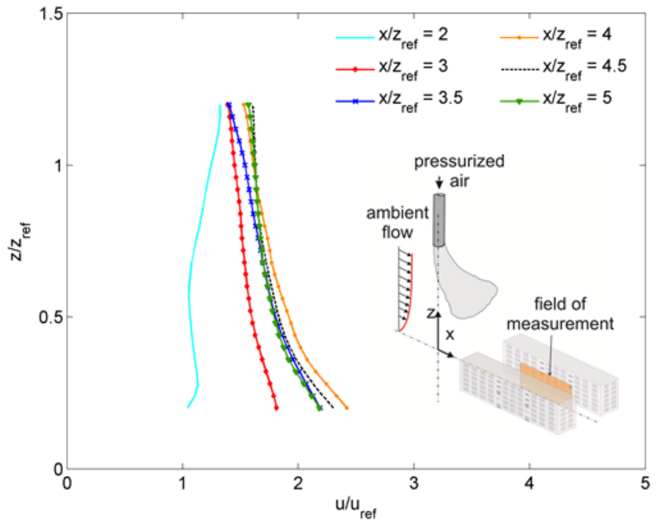
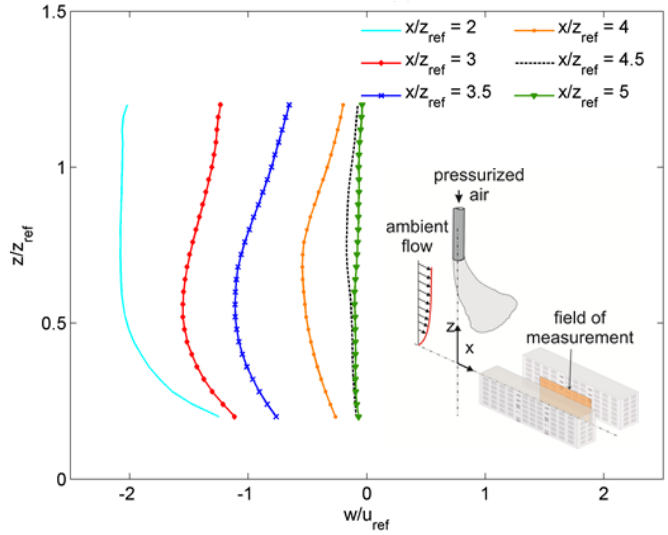


Fig. 6: Horizontal (left) and vertical (right) velocity profiles of the open terrain case - constant wall jet; z_{ref} = 50 mm (i.e. 10 m in nature), $u_{ref} = u(z_{ref})$ of the background flow

As can be inferred from Fig. 6 (right side), the vertical velocity is very strong at the beginning of the measurement area and is in the same order of magnitude as the horizontal component, i.e. the jet enters the measurement field with an angle of about 45°. With increasing x/z_{ref} w diminishes and the horizontal component dominates. In general, an outflow of a downburst or impinging jet is understood as a horizontal flow, accelerating away from the impingement region and propagating over the plate or ground. To determine or quantify an outflow, the outflow is, for our purposes, defined as a region where the vertical component has almost vanished. The height of the outflow is estimated by the level where the velocity u of the impinging jet is 1.5 times greater than the background flow at the same height. The outflow in the open terrain case is, thus, detected for $x/z_{ref} \geq 5$ with a height of about $0.6 \cdot z/z_{ref}$ (i.e. 30 mm).

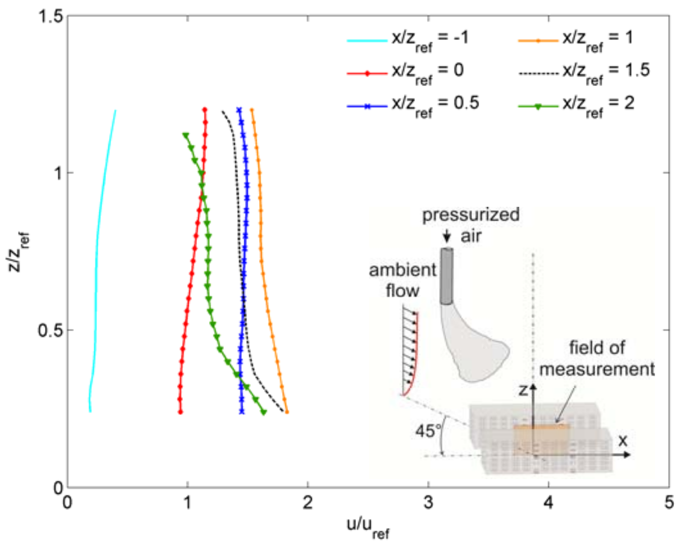
Considering the same configuration with added built structure (street canyon parallel to the atmospheric background flow), it can be seen that the highest horizontal velocities show a different shape, see Fig. 7. Though the highest velocities occur close to the ground, they do not decrease with height as fast as in the open terrain. Furthermore, the maximum velocities are retained over a long distance and no significant decrease of the horizontal velocity can be observed within the measurement field. The vertical component w has a significant maximum at about 0.5 to $0.7 \cdot z/z_{ref}$ over the whole measurement field which is in contrast to the open terrain case. For x/z_{ref} > 5 the vertical component is almost zero and a horizontal outflow arises within the street. The velocity component u is still very strong at all heights, i.e. the outflow extends over the whole street height.





.

Fig. 7: Horizontal (left) and vertical (right) velocity profiles within the street canyon model parallel to the atmospheric background flow (case 2), z_{ref} = 50 mm (i.e. 10 m in nature), u_{ref} = $u(z_{ref})$ of the open terrain background flow; building height H=1,5 z_{ref} (i.e. 15 m in nature)



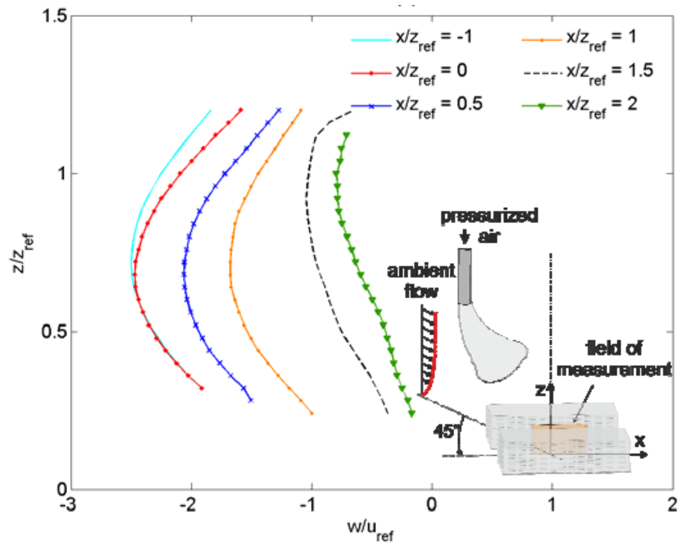


Fig. 8: Horizontal (left) and vertical (right) velocity profiles within the street canyon model with an orientation of β = 45° (case 3), z_{ref} = 50 mm, u_{ref} = $u(z_{ref})$ of the open terrain background flow (case 1).

The flow within the street canyon of β = 45°, see Fig. 8, diverges from the impingement region (that is at $x/z_{ref} \approx -0.5$, see *Fig. 8*) in both directions, though more to the right side (x > 0) which is in flow direction. For clarity, only profiles downstream of the impingement point are depicted. Up to the location of maximum velocity, the horizontal velocity is almost uniform over the height in the accelerating flow ($x/z_{ref} < 1.5$). After this location, the velocity decreases, whereas it decreases faster in the upper part and higher velocities are maintained in the lower part. The maximum vertical velocity occurs at the impingement region at a height of $z/z_{ref} \approx 0.7 - 0.9$.

In order to visualize the interaction of downdrafts and built structure, also flow visualizations have been carried out. Fig. 9 shows an experiment, where a downdraft impinging on a street canyon spreads out. The ambient background velocity was set to nil in this experiment. In contrary to the aforementioned experiments, the spreading of the primary vortex was tracked. As can be seen from the sequence of frames in Fig. 9, the propagation speed within the street canyon is significantly higher than in open and flat terrain.

6. Conclusion

Previous studies showed that downdrafts can cause very high wind speeds near the ground. Since they come from above, their strength is independent of the surrounding roughness and air parcels of high momentum can enter into inner-city areas. It could be demonstrated in the presented paper that street canyons have an additional effect on the near ground flow field of downdrafts. Depending on the orientation of a street canyon relative to the ambient wind, the outflow is higher within the canyon than in open terrain. In the street canyon, the horizontal peak velocities even increase instead of radially decreasing in open terrain. Additionally, regardless of the canyon's orientation, a very strong vertical component is detected within the canyon, that is not considered in

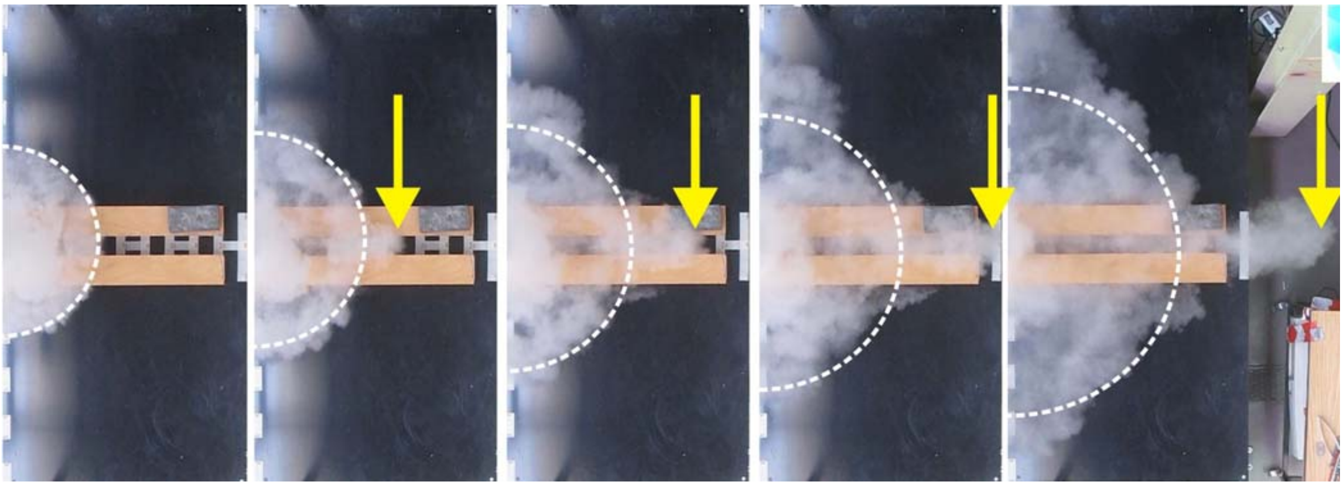


Fig. 9: Visualized downdraft (CO_2 with water droplets) impinges on a street canyon in a simulation experiment; the radial spreading of the primary vortex in the plane is marked with white dashed circles, the faster spreading within the street canyon is marked with yellow arrows; taken from Eggs 2015

most guidelines for wind loadings. This may also cause high pressures in the impingement region due to stagnation. Finally, it should be noted that the experiments presented here were conducted with a steady jet simulating the downdraft. Thus, unsteady effects as the radial spreading of the primary vortex were not investigated. The latter will be performed in following studies within the ConWinG project.

Acknowledgement

The financial support of the Deutsche Forschungsgemeinschaft (DFG) for the presented study (grant no. Ru 345/35-1) is gratefully acknowledged by the authors.

References

ASCE7: Minimum design loads for buildings and other structures, STANDARD by American Society of Civil Engineers, 10/01/2013

Chay, M., Letchford, C., 2002: “Pressure distributions on a cube in a simulated thunderstorm downburst. Part A: stationary downburst observations”, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 90, No. 7, pp. 711-732

DIN EN 1991-1-4, 2010: Eurocode 1, Einwirkungen auf Tragwerke-Teil 1-4: Allgemeine Einwirkungen – Windlasten, DIN Deutsches Institut für Normung e.V.

Dodge, J., Arnold, J., Wilson, G., Evans, J., Fujita, T.T., 1986: The cooperative Huntsville meteorological experiment (COHMEX), Bull. Amer. Meteor. Soc. 67, 417 – 419

Eggs, F., 2015: Bau einer Versuchseinrichtung zur Simulation von Fallböen mit Verifikationsmessungen, BSc-Thesis at the Laboratory of Building- and Environmental Aerodynamics, KIT, Germany

Fujita, T. T. 1979: Objectives, operation, and results of Project NIMROD, *11th Conf. on Severe Local Storms,* Kansas City, MO, Amer. Meteor. Soc., 259–266.

Fujita, T.T., 1981: Tornadoes and Downbursts in the Context of Generalized Planetary Scales. *J. Atmos. Sci.*, **38**, 1511–1534.

Fujita, T.T., 1990: “Downbursts: meteorological features and wind field characteristics”, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 36, pp. 75-86

Hjelmfelt, M.R., 1988: Structure and life cycle of microburst outflows observed in Colorado, J. Appl. Metall. 27, 900–927

Kim, J.,Hangan, H., 2007: Numerical simulations of impinging jets with application to downburstsJournal of Wind Engineering and Industrial Aerodynamics 95, 279–298

Letchford, C., Chay, M., 2002: “Pressure distributions on a cube in a simulated thunderstorm downburst. Part B: moving downburst observations”, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 90, No. 7, pp. 733-753

McCarthy, J., Wilson, J.W., Fujita, T.T., 1982: "The joint airport weather studies project." *Bull. Amer. Meteor. Soc* 63.1, 15-22.

Savory, E. et al., 2001: “Modelling of tornado and microburst-induced wind loading and failure of a lattice transmission tower”, Engineering Structures, Vol. 23, pp. 365-375